PAIR PRODUCTION AND RADIATION EFFECTS IN CLOUDS ILLUMINATED BY GAMMA RAY SOURCES

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ABSTRACT

Many classes of gamma-ray sources, such as gamma-ray bursts, blazars, Seyfert galaxies, and galactic black hole sources are surrounded by large amounts of gas and dust. X-rays and gamma-rays that traverse this material will be attenuated by Compton scattering and photoelectric absorption. One signature of an intervening scattering cloud is radiation-hardening by electrons that have been scattered and heated by the incident radiation, as illustrated by a Monte Carlo calculation. Compton scattering provides backscattered photons that will attenuate subsequent gamma rays through $\gamma\gamma$ pair-production processes. We calculate the pair efficiency for a cloud illuminated by gamma-ray burst radiation. An analytic calculation of the flux of X-rays and gamma rays Thomson scattered by an intervening cloud is presented. Illuminated clouds near GRBs will form relativistic plasmas containing large numbers of electron-positron pairs that can be detected within $\sim$ 1-2 days of the explosion before expanding and dissipating. Localized regions of pair annihilation radiation in the Galaxy could reveal gamma-ray sources embedded in dense clouds, or sites of past GRB explosions.

Key words: positrons; gamma rays; nonthermal radiation processes.

1. INTRODUCTION

If a central source of hard X-rays and soft gamma rays is surrounded by Thomson-thick scattering clouds, then the electrons in the cloud will be heated to the Compton temperature of the incident radiation, and hard X-rays will be backscattered. Radiation that passes through these hot scattering clouds will have their soft X rays scattered to higher energies (Dermer & Böttcher, 2000). Soft gamma-rays that pass through the cloud will be subject to pair-production through $\gamma\gamma$ interactions (Madau & Thompson, 2000; Mészáros et al., 2001). These pairs can annihilate to form a broadened 0.511 MeV line within the hot relativistic plasma, or will diffuse into the interstellar medium to produce sites of localized annihilation radiation. The Compton-scattered radiation is detected later at lower flux levels (Madau et al., 2000). Such systems provide potential targets for *INTEGRAL*.

A simple generalization of standard compactness arguments (Fabian et al., 1986) for an illuminated cloud characterizes the condition when backscattered pair-production interactions must be considered. The process of $\gamma\gamma$ pair production attenuation begins to be important when $n_\gamma \sigma_{\gamma\gamma} r \gtrsim 1$, where $n_\gamma \simeq L_\gamma/(4\pi r^2 m_e c^3)$ is the number density of γ-ray photons with energies $\gtrsim 1$ MeV, L_γ is the γ-ray luminosity, r is the radius of the cloud, and $\sigma_{\gamma\gamma}$ is the pair production cross section. Because $\sigma_{\gamma\gamma} \approx \sigma_{\rm T}$ near threshold, a system is compact when $L_\gamma/r \gtrsim 4\pi m_e c^3/\sigma_{\rm T} = 4.6 \times 10^{29}$ ergs s^{-1} cm^{-1}. We generalize this result to determine when a cloud, illuminated by a γ-ray source a distance d from the cloud, becomes compact. The compactness condition depends on the width Δx of the illuminating photon front. If $\Delta x \gg r$, then the number density of the scattered radiation field is $n_\gamma \approx L_\gamma \tau_{\rm T}/(4\pi d^2 c \cdot m_e c^2)$, whereas if $\Delta x \ll r$, then $n_\gamma \approx L_\gamma \tau_{\rm T}(\Delta x/r)/(4\pi d^2 c \cdot m_e c^2)$. Consequently, an illuminated cloud with $\tau_{\rm T} \lesssim 1$ is compact if

$$L_\gamma \gtrsim (\frac{d}{r})^2 \, \frac{4\pi m_e c^3}{\sigma_{\rm T}} \, (\frac{r}{\tau_{\rm T}}) \begin{cases} 1\,, & \text{for } \Delta x \gg r \\ r/\Delta x & \text{for } \Delta x \ll r. \end{cases} \quad (1)$$

For GRBs which produce photon fronts $\Delta x \sim$ 10-100 lt-s, Thomson-thick clouds with radii $r = 10^{15} r_{15}$ cm located $\sim 10^{16}$ cm away from the GRB source will be compact when $L_\gamma \gtrsim 10^{50}$ ergs s^{-1}. Smaller gamma-ray powers are required for persistent sources. In this paper, we focus on GRB/cloud interactions, in view of evidence (Amati et al., 2000) that such sources have highly metal enriched clouds with large column densities in their vicinity.

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2. BLAST-WAVE CLOUD INTERACTION

A wave of photons impinging on a cloud located $10^{16}d_{16}$ cm from the GRB source will photoionize and Compton-scatter the ambient electrons to energies characteristic of the incident γ rays (Madau & Thompson, 2000; Dermer & Böttcher, 2000). For a plasma cloud with a width of $r \cong 3\times 10^4 r_{15}$ lt-s, radiation effects must be treated locally. Besides making pairs through $\gamma\gamma$ attenuation with backscattered photons, the nonthermal electrons and pairs will Compton scatter successive waves of photons, thereby modifying the incident spectrum.

GRBs produce a temporally-evolving spectrum of nonthermal synchrotron photons with energy $\epsilon = h\nu/m_ec^2$ that can be parameterized by the equation

$$\Phi(\epsilon) = \frac{L_p(1+\upsilon/\delta)}{4\pi d^2 m_e c^2\epsilon_0^2}\,\Big[\frac{1}{(\epsilon/\epsilon_0)^{2-\upsilon}+(\upsilon/\delta)(\epsilon/\epsilon_0)^{2+\delta}}\Big] \tag{2}$$

where ϵ_0 is the photon energy of the peak of the νF_ν spectrum, L_p is the peak spectral power, and υ and δ are the νF_ν spectral indices at energies $\epsilon \ll \epsilon_0$ and $\epsilon \gg \epsilon_0$ respectively. The quantities $L_p = L_p(t)$ and $\epsilon_0 = \epsilon_0(t)$ depend upon time t, and $\epsilon_0 \sim 1$ during the prompt γ-ray luminous phase of a GRB. As nonthermal synchrotron photons from a GRB impinge on the atoms in the cloud, electrons will be Compton-scattered by the high-energy radiation. The time scale for an electron to be Compton-scattered by a photon is $t_T(s) \approx 15(1+z)d_{16}^2\epsilon_0/L_{50}$, assuming that all Compton scattering events occur in the Thomson limit. The Klein-Nishina decline in the Compton cross section will increase this estimate by a factor of $\sim$ 1-3, depending on the incident spectrum. Most of the electrons in the cloud will therefore be scattered to high energies during a very luminous ($L_{50} \gg 1$) GRB, or when the cloud is located at $d_{16} \ll 1$.

Electrons are Compton-scattered on the Thomson time scale to form a hard spectrum that turns over at kinetic energies of $\gtrsim 500\times\min(1,\epsilon_0^2)$ keV. For a GRB with $\epsilon_0 \sim 1$, most of the kinetic energy is therefore carried by nonthermal electrons with energies of $\sim$ 500 keV. Successive waves of photons that pass through this plasma will continue to Compton-scatter the nonthermal electrons. Only the lowest energy photons, however, will be strongly affected by the radiative transfer because both the Compton scattering cross section and energy change per scattering is largest for the lowest energy photons.

Fig. 1 shows Monte Carlo simulations of radiation spectra described by eq. (2) that pass through a hot electron scattering medium. For simplicity, we approximate the hard nonthermal electron spectrum by a thermal distribution with temperatures of 100 and 300 keV, and neglect pair production processes. The electron temperature is chosen so that the mean electron kinetic energy is less than the Compton temperature of the incident radiation. These calculations show that the lowest energy photons of the primary synchrotron spectrum are most strongly scattered,

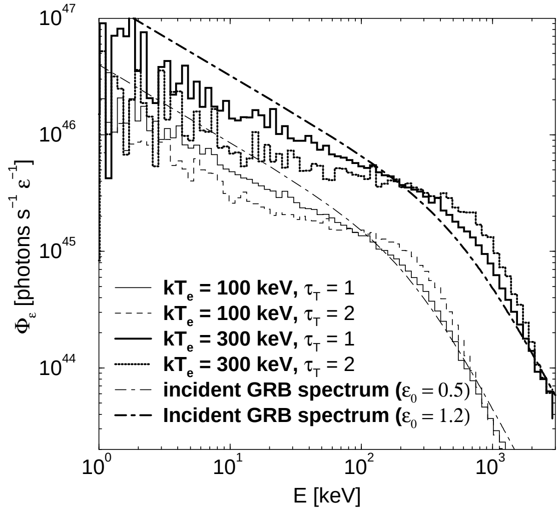

Figure 1. Radiation transfer effects on GRB emission that passes through electrons energized by an earlier portion of the photon front. The intrinsic spectra, from eq.(2) with $\upsilon = 2/3$ and $\delta = 0.2$, are shown by the thin and thick curves for $\epsilon_0 = 0.5$ and $\epsilon_0 = 1.2$, respectively. The nonthermal electrons are approximated by a thermal distribution with temperatures of 100 keV (thin histograms) and 300 keV (thick histograms), and Thomson depths $\tau_T = 1$ $\tau_T = 2$ as labeled. Photon spectral indices α_X calculated at 50 keV are 0.54 ($T = 100$ keV, $\tau_T = 1$), 0.45 ($T = 300$ keV, $\tau_T = 1$), 0.28 ($T = 100$ keV, $\tau_T = 2$), and 0.16 ($T = 300$ keV, $\tau_T = 2$).

and that the "line-of-death" problem of the synchrotron shock model of GRBs (Preece et al., 1998; Crider & Liang, 1999) can be solved by radiation transfer effects through a hot scattering cloud with $\tau_T \gtrsim$ 1-2. Radiation transfer effects by intervening clouds may likewise harden the intrinsic spectrum of other hard X-ray and gamma-ray sources.

3. PAIR EFFICIENCY CALCULATIONS

Following the initial wave of photons, successive photon fronts also encounter the back-scattered radiation, which will lead to $\gamma\gamma$ attenuation and pair production (Thompson & Madau, 2000). Here we use the analytic model of Dermer, Chiang, & Böttcher (1999), eq. (2), for the spectral and temporal evolution of the GRB spectrum. The parameters are total energy $E_0 = 10^{52}\,E_{52}$ ergs, initial bulk Lorentz factor $\Gamma_0 = 300\Gamma_{300}$, surrounding medium density $n_0 = 100\,n_2$ cm^{-3}, radiative regime parameter $g = 1.6$, B-field and electron-acceleration parameter $q = 2\times 10^{-4}$, and we let $\upsilon = 4/3$ and $\delta = 0.5$. The geometrical thickness of the cloud is $r = 10^{15}\,r_{15}$ cm and its Thomson depth $\tau_T \sim 1$. We calculate the space- and time-dependent $\gamma\gamma$ opacity due to radiation backscattered by the cloud into the path of the prompt radiation, and the corresponding rate of pair production. For this purpose, we assume that the cloud material is ionized instantly at the onset

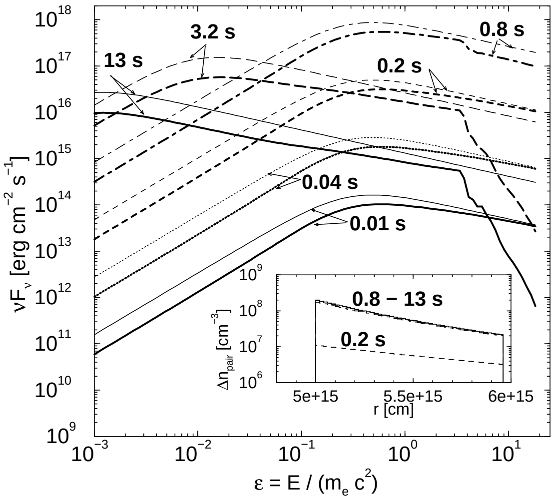

Figure 2. Spectral evolution of the pair and Compton attenuated GRB radiation. Inset shows the temporal evolution of the secondary pair density as a function of cloud radius. Parameters: $d_{16} = 0.5$, $r_{15} = 1$, $\tau_T = 1$, $E_{52} = \Gamma_{300} = n_2 = 1$.

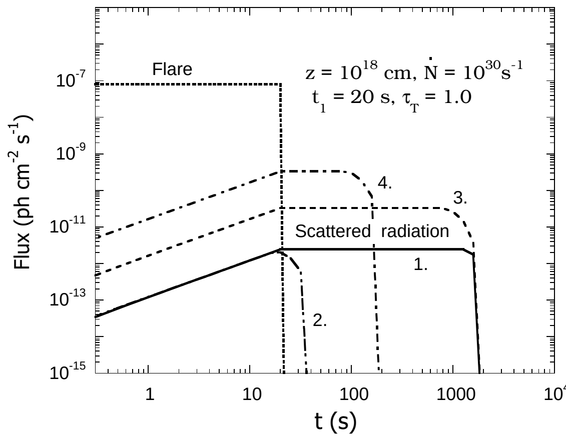

Figure 3. Direct and Thomson-scattered photon flux for a Thomson thick ($\tau_{\rm T} = 1$) cloud illuminated by a 20 second flare. The flux is normalized to a detector at 10^{18} cm from the source. Curve 1: $r = 10^{15}$ cm, $d = 10^{16}$ cm; Curve 2: $r = 10^{14}$ cm, $d = 10^{16}$ cm; Curve 3: $r_1 = 2.5 \times 10^{14}$ cm, $d = 7.5 \times 10^{14}$ cm; Curve 4: $r_1 = 2.5 \times 10^{13}$ cm,$r_2 = 7.5 \times 10^{13}$ cm.

of the GRB, and that the GRB radiation instantly heats the free electrons to the Compton equilibrium temperature. The formalism used to calculate the $\gamma\gamma$ opacity is largely analogous to the calculation of Böttcher & Dermer (1995) for the case of $\gamma\gamma$ attenuation in blazars. The effect of Compton scattering on the transmitted GRB radiation is evaluated using an appropriate average of the effective Compton scattering cross section over the thermal distribution of electrons and pairs at any given radius.

Fig. 2 shows an example of such a calculation with typical GRB parameters (Böttcher & Dermer, 2000). The efficiency for making pairs in this example (defined as the fraction of incident radiation energy transformed into pairs) is 0.43 %. This pair efficiency is large enough that GRBs could make a substantial contribution to the annihilation glow of the Milky Way, which would be concentrated near sites of an earlier GRB. Fig. 2 indicates that although the actual pair efficiency and the relative number of pairs versus background thermal electrons ($n_{\rm e,cloud} = 1.5 \times 10^9$ cm^{-3}) may be rather low, both the effects of $\gamma\gamma$ attenuation of high-energy photons and Compton upscattering of low-energy photons can become quite significant.

4. SCATTERED FLUX FROM A THOMSON-THICK CLOUD

Here we outline a derivation of pulse scattering and echo effects that occur when a photon front passes through a scattering cloud, with Thomson depth $\tau_{\rm T} \lesssim 1$ (Madau et al., 2000; Böttcher & Dermer, 2000), that lies along the line-of-sight to the observer. Photons that are scattered by an intervening cloud will be detected later at a reduced flux. Following the treatment of Böttcher & Dermer (1995), let $\dot{N}_{ph}(\epsilon, \Omega; t_*) d\epsilon d\Omega$ represent the differential number of photons with dimensionless photon energy ϵ between ϵ and $\epsilon + d\epsilon$ that are directed into solid angle interval $d\Omega$ in the direction Ω at time t_* is the frame of the emitter. If, for simplicity, we assume isotropic emission from the source, then $\dot{N}_{ph}(\epsilon; t_*) = 4\pi \dot{N}_{ph}(\epsilon, \Omega; t_*)$. The photon emissivity due to photons that are isotropically Thomson scattered by stationary material with density $n_e(\mathbf{r})$ at location $\mathbf{r}$ is $\dot{n}_{ph}(\epsilon; \mathbf{r}, t_*) = n_e(\mathbf{r}) \sigma_{\rm T} \dot{N}_{ph}(\epsilon, t_* - r/c)/(4\pi r^2)$. The photon density received at a location along the line of sight of the cloud at a distance z from the central source and at time t is $n_{ph}(\epsilon; z, t) = \int d^3\mathbf{r}\, \dot{n}_{ph}(\epsilon; t - x/c)/(4\pi x^2 c)$, where $x = \sqrt{r^2 + z^2 - 2rz\mu}$, and μ is the cosine of the angle between the directions to the received flux and the scattering event.

We assume that a scattering cloud lies along the line-of-sight between the source and observer, and describe it with a special geometry

$$n_e(r, \mu) = \begin{cases} n_e^0\ , & \text{for } r_1 \le r \le r_2 \text{ and } \mu_0 \le \mu \le 1 \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

where $\sin\theta_0 = (r_2 - r_1)/(r_2 + r_1)$ and $\theta_0 = \arccos(\mu_0)$. For a flare of constant intensity that lasts for a time t_1, we obtain for the scattered flux

$$\phi_{sc}(\epsilon; z, t) = \frac{n_e^0 \sigma_{\rm T} \dot{N}_{ph}(\epsilon)}{8\pi} \int_{\mu_0}^{1} \frac{d\mu}{\mu}\ \left(\frac{1}{z - R_2\mu} - \frac{1}{z - R_1\mu}\right)\ , \tag{4}$$

where $R_1 = \max[r_1, (ct - ct_1 - z)/(1-\mu)]$ and $R_2 = \min[r_2, (ct - z)/(1-\mu)]$.

Fig. 3 shows calculations using eq. (4) for the direct and scattered flux from a 20 s flare. The basic features of these calculations can be understood by

noting that the scattered flux persists for a time

$$t_{sc} = \max(t_1, \frac{r^2}{2dc}) \ , \tag{5}$$

and that the ratio of the scattered flux to the direct flux is

$$\frac{\phi_{sc}}{\phi_d} \cong \frac{c}{2d}\, \tau_{\rm T} t_1 \ , \tag{6}$$

for $\tau_{\rm T} \lesssim 1$. An interesting implication is that the scattered flux is comparable in intensity to the direct flux only when the scattering clouds are within a distance $\sim ct_1$ of the central source. When the clouds are extremely optically thick with $\tau_{\rm T} \gg 1$, the central source is strongly attenuated and the scattered radiation will make a larger contribution.

5. OBSERVATIONAL SIGNATURES OF ILLUMINATED CLOUDS

We have considered three potentially observable effects of gamma-ray sources that illuminate nearby Thomson-thick clouds:

1. Spectral hardening of radiation that passes through Compton-heated gas;
2. Formation of pairs when γ rays interact with backscattered photons; and
3. Scattered flux that is detected at later times.

We (Dermer & Böttcher, 2000) have proposed that the first effect could account for unusually hard spectra detected in $\sim$ 5-10% of GRBs, thereby explaining exceptions to the nonthermal synchrotron shock model of GRBs. *INTEGRAL* could observe such effects in serendipitous GRBs. Given a full sky GRB rate of $\sim$ 900 yr^{-1}, SPI might detect $\sim$ 6 GRBs yr^{-1} within its fully coded FoV and $\sim$ 24 GRBs yr^{-1} within its partially-coded FoV. Searches for this effect can be made through spectral analyses of these GRBs.

Production of e$^+$-e$^-$ pairs through the second effect will occur in the vicinity of compact γ-ray sources that have large amounts of gas surrounding them. The best prospects for INTEGRAL would be to search for annihilation radiation from soft γ-ray and unidentified EGRET sources in the disk of the Galaxy. GRBs will make a significant contribution to the annihilation glow of the Galaxy. The time-averaged kinetic energy of GRB sources into an L* galaxy such as the Milky Way is $10^{40\pm1}$ ergs s^{-1} Dermer (2000). As shown here, backscattered pair production processes can transform $\sim$ 0.1-1% of the γ rays into e$^+$-e$^-$ pairs with MeV energies. Given the additional ~ 10% efficiency for converting the kinetic energy of GRBs into γ rays, we see that GRB sources produce a time-averaged injection rate of $\sim 10^{41}$-10^{43} e$^+$ s^{-1} into the Milky Way that could contribute substantially to the Galactic 0.511 MeV intensity of the Galaxy (Dermer & Murphy, these proceedings). Because of the rarity and energy of GRBs, these would most likely be detected as localized hot spots of annihilation radiation surrounded by a hypernova remnant signaling an earlier GRB.

Compton echoes from distant scattering clouds may be detectable in the afterglow phase of GRBs (Madau et al., 2000), and reverberation effects due to Thomson scattering in heavily obscured Seyfert 2 galaxies could be observable with *INTEGRAL*. As we have seen, scattered fluxes from short pulses of high-energy radiation would be difficult to detect from clouds in the vicinity of GRB sources unless $\tau_T \gg 1$. These clouds, would, however, be heated to temperatures of 100 keV - several MeV to form relativistic plasmas that would expand and cool. The cooling, expanding plasma would produce a broad pair annihilation feature (Guilbert & Stepney, 1985). Hot plasmas formed by nearby GRBs at $z \sim 0.1$ would be easily detectable with the *INTEGRAL* and Swift missions (Dermer & Böttcher, 2000).

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